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# Knemometry in assessment of linear growth

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SUMMARY A rigorously designed auxological study was carried out to assess the operational characteristics of the knemometer and the value of short term lower leg and height measurements in estimating and predicting rates of linear growth. Measurements were made on 18 normal children monthly for six months and on six normal children weekly for six weeks. Six other children measured weekly underwent tonsillectomy after three weeks to determine the effect of stress on growth. The measurement protocol permitted estimations of both inter- and intraobserver variation.

Knemometry is a sensitive, precise, and robust technique that enables accurate measurements to be made of the lower leg by interchangeable observers. The lower leg does not grow smoothly and variations in growth rate seen in both healthy children and children with transient intercurrent stress limit the practical clinical value of knemometry to the measurement of linear growth in the short term.

The knemometer (Fig. 1) is an instrument designed to measure the length of the lower leg with great accuracy,[1] thereby permitting the calculation of rates of linear growth at time intervals as short as daily[2] or intradaily.[3] The availability of this technique has led to speculation that it may be useful in measuring the growth response to different forms of treatment in shorter time intervals than has been possible hitherto. The only published assessment of the operational characteristics of the knemometer is that of the inventors,[1] and no study has been reported describing the relation of lower leg growth to that of overall height or of the value of short term measurements to predict growth in the longer term. The machine is expensive and the technique specialised and fairly time consuming. We have therefore performed an audit of knemometry to assess its strengths and weaknesses as a clinical research tool.

## Methods

The measurers were an auxologist (M), two research nurses (C and S) and a paediatrician (J), all of whom had been instructed in the use of the knemometer by its inventor, Dr I M Valk. All measurements were made between April and September 1985 in the action laboratory at our hospital. Every time a child attended the laboratory single measurements were made in the following sequence: weight (Avery beam balance), standing and sitting height[4] (Harpenden Stadiometers), and mid-triceps and subscapular skinfold thickness (Holtain calipers). Then followed measurements of lower leg length by knemometry.

The child was placed on the adjustable seat with the position of the feet on the measurement table determined by an individually drawn template used at each visit. When the child was comfortable and relaxed a horizontal measuring plate connected to an electronic Sony Digiruler (Sony Magnescale Inc, Japan; measurement interval 0·1 mm) was placed on the upper surface of the knee. The child was then moved backwards and forwards on the frictionless chair mount and the leg moved from side to side until a stable maximum reading was achieved. Six sequential determinations of tibial length were made at each visit in the monthly study and four at each visit in the weekly study, the child leaving the seat and walking a few steps between each measurement.

At each attendance the child was measured by two observers working sequentially and totally independently. The same observer pair then measured the child at each subsequent visit. At the first visit each observer positioned the child on the knemometer and noted the settings, which were then used by that observer in all subsequent visits to allow reproducible placing of the child. On 27 occasions the designated observer was absent and a substitute observer used the designated observer's settings to position the child. All readings of

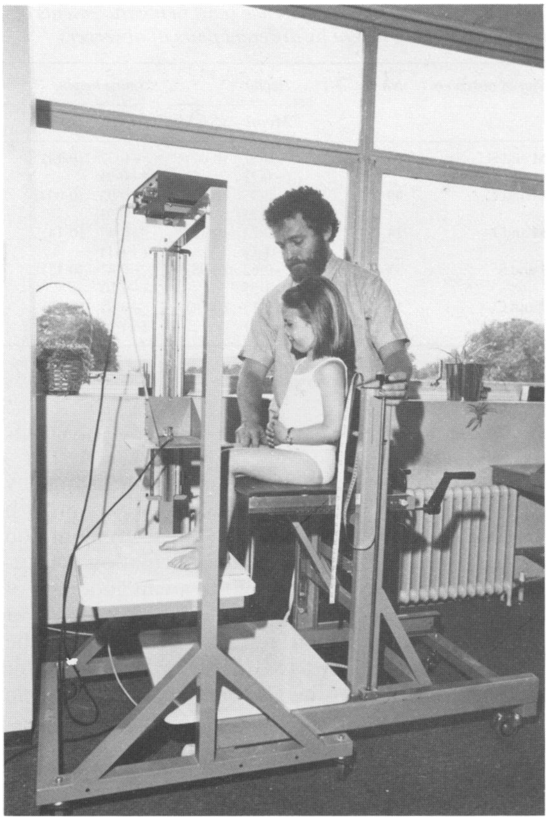

Fig. 1 *The knemometer in use.*

conventional auxology and knemometry were recorded on counterfoil and stored immediately in sealed envelopes until analysis at the end of the study. At each visit notes were made on the child's activities and any symptoms or illness that had occurred since the last visit. All measurements on a child were made on the same weekday between 1500 and 1800h to coincide with the described intradaily plateau of postural change in lower leg length.[3] No child defaulted a planned measuring visit. Informed parental consent was obtained in all cases and the study was approved by the hospital ethical committee.

## Subjects

All the children were white local residents from the middle and professional classes.

**Monthly measurements.** Six normal boys (aged 5·5 to 9·8 years) and 12 normal girls (aged 5·5 to 10·5 years) were measured for six months.

**Weekly measurements.** Six children (three boys and three girls aged 7·0 to 10·0 years) were measured for six weeks and once more 12 weeks later. They were all in good health at the start of the study but by chance all three boys had mild self limiting illnesses during the study, whereas the girls remained well. Six further children (four girls and two boys aged 3·7 to 13·4 years) were measured weekly for three weeks before and after tonsillectomy.

## Results

**Variation in measurement within and between observers.** The sets of six knemometry readings made at monthly intervals by the four observers were analysed. The number of sets for each observer was: M 83, J 60, C 56, and S 53. The mean coefficients of variation for a set of six readings were 0·09, 0·08, 0·10, and 0·10%, respectively. The maximum coefficient of variation observed was 0·25%. The coefficient of variation for an observer did not change with increasing experience, indicating that a learning phenomenon did not occur during the six month study. The reproducibility of knemometry measurements experienced in the monthly study led to the decision to reduce the number of readings to four in a set in the study of normal children measured weekly. There were 72 sets of four readings made by the four observers in which the maximum coefficient of variation was 0·13%.

Measuring the children by pairs of observers made it possible to analyse if there was a systematic variation in estimates of lower leg length between members of a pair. In 126 pairs of measurements there were eight in which both observers obtained the same result. If the null hypothesis is that observer 'a' measures greater than observer 'b' randomly then a>b on 59 occasions and vice versa. In fact a>b occurred on 109 occasions, indicating a highly significant ($p<0·001$) systematic variation. Inspection of the two most common measuring pairs showed that the variation was specific for each child but not for each observer (Table 1), leading to the conclusion that the difference between observers in the estimate of lower leg length was a function of the initial, and therefore subsequent, positioning of the child on the knemometer by that observer. This interpretation was reinforced by the observation that on the 27 occasions when an observer substituted for an absent colleague the measurement of lower leg length was in harmony with the previous and subsequent measurements made by the original observer.

In contrast to the systematic variation in measurement of lower leg length, there was no significant

Table 1 *Maximum difference (cm) between the two principal pairs of observers for measurements of height, sitting height, and lower leg length in individual children*

| Pair of observers | Measurement | | |
|---|---|---|---|
| | Height | Sitting height | Lower leg |
| M and C | 1·4 (1) | 1·6 (2) | 0·12 (6) |
| | 0·5 (0) | 1·4 (3) | 0·11 (7) |
| | 0·4 (0) | 1·1 (4) | 0·12 (5) |
| | 1·1 (3) | 1·0 (2) | 0·24 (4) |
| | 1·0 (1) | 1·4 (2) | 0·09 (7) |
| | 0·3 (0) | 1·3 (3) | 0·12 (3) |
| | 0·5 (2) | 0·5 (4) | 0·07 (4) |
| Mean (SD) | 0·7 (0·4) | 1·2 (0·4) | 0·12 (0·05) |
| J and S | 1·7 (2) | 1·6 (0) | 0·07 (7) |
| | 1·2 (0) | 0·7 (1) | 0·11 (0) |
| | 1·4 (1) | 2·6 (2) | 0·04 (0) |
| | 0·6 (0) | 1·4 (0) | 0·28 (1) |
| | 1·4 (2) | 3·6 (3) | 0·28 (5) |
| Mean (SD) | 1·3 (4·0) | 2·0 (1·0) | 0·16 (0·12) |

The figures in parentheses (except for the standard deviation values) show the number of times out of seven when the first observer measured higher than the second observer.

Table 2 *Mean (SEM) difference (cm) in measurements of height and sitting height by different pairs of observers*

| Pair of observers | No | Height | | Sitting height | |
|---|---|---|---|---|---|
| | | Mean | (SEM) | Mean | (SEM) |
| M and S | 14 | +0·32 (−0·7) | (0·07)** | −0·37 (+0·9) | (0·14)* |
| M and C | 49 | −0·35 (−1·3) | (0·05)** | −0·03 (±0·9) | (0·004) |
| M and J | 14 | +0·23 (−1·1) | (0·12) | +0·47 (+1·1) | (0·14)* |
| J and S | 35 | −0·62 (−1·5) | (0·08)** | −0·47 (−2·0) | (0·15)* |
| J and C | 14 | −0·15 (+1·6) | (0·14) | +0·02 (+1·6) | (0·19) |

Results show the measurement made by the first observer minus that made by the second observer. Largest difference between observers is shown in parentheses.
*$p<0·05$; **$p<0·001$.

difference between observers in the estimates of increment in lower leg length at monthly intervals. The pair of observers made identical determinations of lower leg length increment in five of 108 estimations and in the remainder observer 'a' estimated a greater increment than observer 'b' in 49 of 103 estimations, which did not differ significantly from that expected by chance, which was 51 of 103. These results led to the conclusion that knemometry is a precise technique for measuring increments in lower leg length at monthly intervals and that trained observers can substitute for each other so long as the child is positioned consistently for each measurement.

Height and sitting height were measured once only at each visit so no estimate of intraobserver variation could be made. When the measurements of height and sitting height were analysed by the two principal pairs of observers (Tables 1 and 2) there was a consistent difference for height between observers M and C and observers J and S that was observer specific but not child specific. The maximum difference between two observers in seven measurements on one child was 1·6 cm for height and 2 cm for sitting height, which illustrates the greater difficulty in measuring sitting height. Analysis of measurements of height and sitting height by the five observer pairs showed significant systematic differences in six out of 10 pairings (Table 2). These results confirmed that measurement of height and sitting height are more prone to systematic observer variation than is knemometry.

**Calculation of linear growth velocities.** The seven measurements of lower leg length, height, and sitting height made on the 18 normal children by each observer were used to calculate rates of growth by linear regression of each measurement on decimal age (Table 3). The same calculation permitted an estimate to be made of the mean goodness of fit of the three derived velocities by each observer (Table 4), from which it can be seen that the professional auxologist (M) was the best measurer of height and sitting height but that there was no significant difference between the four observers' skill in knemometry. The overall goodness of fit for lower leg length was some four times better than that for height or sitting height, reflecting the precision of knemometry.

The relation between lower leg and height measurement was examined by correlating the derived height (H) and lower leg (LL) velocities. The resulting equations for the four observers were:

M: $H=2·75\ LL-0·1$ ($n=11$, $r=0·76$);
J : $H=1·49\ LL-10·8$ ($n=9$, $r=0·32$);
C: $H=1·43\ LL+2·7$ ($n=9$, $r=0·62$);
S : $H=1·84\ LL+2·3$ ($n=7$, $r=0·52$).

These show that measurement of lower leg length was an indifferent and unpredictable estimator of growth in height. Not surprisingly, lower leg length was an even poorer predictor of growth in sitting height (results not shown).

From the results presented in Table 3 it was possible to calculate the percentage variation between the two principal pairs of observers M and C and J and S in their estimates of height or lower leg velocity. For example, for case 11 the estimate of height velocity by J was 5·1 cm/year and by S 6·6 cm/year. The difference between J and S (1·5 cm/year) expressed as a percentage of the mean velocity (5·85 cm/year) was 26%. The mean (SEM) difference in height velocity for all five subjects made by J and S was 16 (3)% and for lower leg

Table 3 *Velocity (cm/year) for height, sitting height, and lower leg calculated for each case and each observer*

| Case No | Observer M Height | M Sitting height | M Lower leg | J Height | J Sitting height | J Lower leg | C Height | C Sitting height | C Lower leg | S Height | S Sitting height | S Lower leg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | 7·5 | 3·0 | 2·57 | 6·5 | 1·5 | 2·66 | | | |
| 2 | | | | 8·9 | 5·7 | 2·13 | 5·8 | 2·6 | 2·65 | | | |
| 3 | 7·0 | 5·8 | 2·00 | | | | | | | 6·1 | 8·8 | 2·16 |
| 4 | 5·2 | 2·1 | 1·81 | | | | 6·0 | 1·5 | 1·54 | | | |
| 5 | 4·6 | 2·0 | 1·84 | | | | | | | 5·1 | 3·3 | 1·84 |
| 6 | 5·7 | 2·5 | 2·03 | | | | 5·5 | 4·2 | 1·90 | | | |
| 7 | 5·3 | 2·0 | 2·29 | | | | 5·2 | 1·5 | 2·27 | | | |
| 8 | 6·5 | 1·0 | 2·01 | 8·5 | 4·5 | 1·96 | | | | | | |
| 9 | 5·5 | 2·2 | 2·20 | 7·8 | 4·6 | 2·09 | | | | | | |
| 10 | 5·4 | 2·2 | 2·30 | | | | 5·4 | 2·4 | 2·49 | | | |
| 11 | | | | 5·1 | 3·0 | 2·34 | | | | 6·6 | 6·8 | 2·35 |
| 12 | 6·0 | 3·6 | 2·00 | | | | 5·3 | 3·3 | 2·05 | | | |
| 13 | 9·1 | 5·9 | 3·04 | | | | 8·7 | 4·4 | 3·08 | | | |
| 14 | | | | 8·0 | 3·6 | 2·08 | | | | 7·2 | 4·3 | 1·90 |
| 15 | | | | 7·2 | 4·3 | 1·91 | | | | 6·2 | 4·6 | 1·99 |
| 16 | | | | 8·5 | 5·6 | 2·57 | | | | 7·8 | 5·9 | 2·96 |
| 17 | | | | 5·9 | 2·6 | 2·53 | | | | 7·2 | 8·1 | 1·99 |
| 18 | 5·4 | 1·5 | 2·01 | | | | 5·8 | 0·1 | 1·99 | | | |

Velocities were calculated from the linear regression of seven monthly measurements on decimal age.

Table 4 *Mean (SD) goodness of fit of derived velocities (cm/year) of height, sitting height, and lower leg length analysed by observer*

| Velocity | Observer M | J | C | S |
|---|---|---|---|---|
| Height | 0·18 (0·06) | 0·33 (0·08) | 0·29 (0·11) | 0·39 (0·13) |
| Sitting height | 0·18 (0·06) | 0·47 (0·19) | 0·61 (0·36) | 0·48 (0·26) |
| Lower leg | 0·06 (0·01) | 0·07 (0·01) | 0·06 (0·01) | 0·08 (0·05) |

Goodness of fit was calculated as the square root of the residual mean square of the seven observations used to calculate the velocity.

velocity was 12 (4)%. For M and C the results on seven subjects were 5 (1)% for height velocity and 5 (2)% for lower leg length velocity. These results show the difference between the two pairs of measurers but more importantly also show that lower leg length velocity calculations were not more reproducible within a pair of observers than were height velocity calculations.

The power of measurements of lower leg length or total height over periods of less than six months to predict the overall six monthly growth velocity calculated from all seven observations is analysed in Table 5. Observations made by the best measurer on 11 normal children were used. The results show that there is little difference between the reproducibility of lower leg and height velocities and that measurements of either made monthly over five months will predict the six monthly velocity within 15% in roughly 97% of cases. Over four months the prediction widens to 18·6% (mean (2 SD)) for lower leg velocity and 28·8% for height velocity. Shorter time intervals produced even poorer predictions.

**The weekly growth of normal children.** Measurements of lower leg length every week in the six normal children are shown in Figure 2. The parallelism of the records made by each pair of observers is

Table 5 *Predictive value of lower leg and height velocities based on observations made at monthly intervals*

| Measurement period (months) | No of measurements | Mean (SD) deviation from reference velocity (%) Lower leg | Height |
|---|---|---|---|
| 5 | 6 | 6·4 (4·5) | 5·5 (3·8) |
| 4 | 5 | 8·8 (4·9) | 11·4 (8·7) |
| 3 | 4 | 15·6 (11·3) | 18·3 (14·4) |
| 2 | 3 | 28·7 (23·7) | 21·8 (11·3) |
| 1 | 2 | 50·8 (46·2) | 52·2 (34·6) |

The figures are obtained from the 11 children measured by the most accurate observer (M). The reference velocity is that calculated from seven monthly observations, and the percentage deviation is defined as the difference between the reference velocity and the observed velocity.

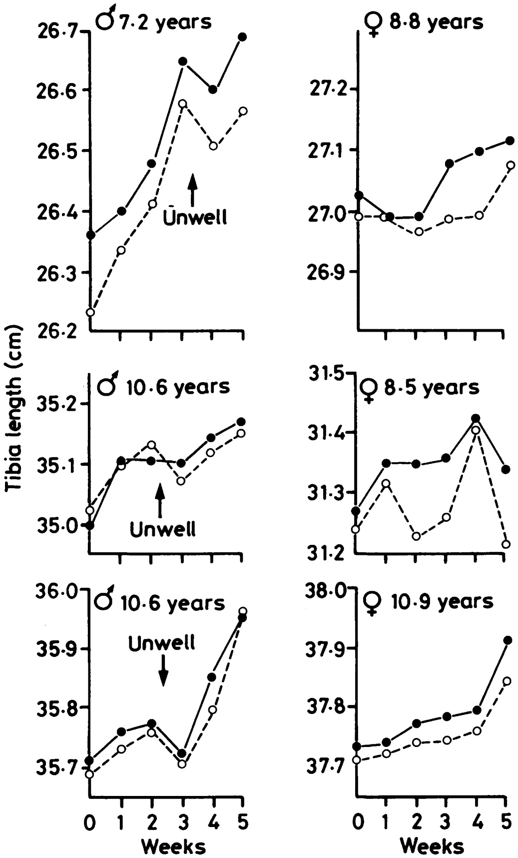


Fig. 2 *Graphs showing lower leg length of six normal children measured by knemometry weekly by two independent observers. The three boys (shown on the left) had mild self limiting illnesses indicated by the arrow. The three girls (shown on the right) were asymptomatic.*

evident as well as the uneven nature of lower leg growth. Each of the three boys suffered a mild self limiting illness during the study, and this coincided with a decrease in lower leg length. Despite the three girls being asymptomatic, they too had uneven lower leg growth.

Each of the six children returned for a final measurement of lower leg length and height three months later. This permitted a comparison to be made between the estimate of growth velocity from seven measurements at weekly intervals with an estimate made from two measurements 12 weeks apart (at six and 18 weeks). When the predicted lower leg velocity (measured from weeks 0 to 6) was expressed as a ratio of the subsequent actual velocity (weeks 6 to 18) the values were: 0·57, 0·90, 1·45, 1·64, 1·76, and 3·2, with a mean of 1·58. When predicted height velocity was expressed in this way the values were: 0·37, 0·38, 0·52, 0·55, 0·57, and 0·93, with a mean of 0·56. Averaging the results from a pair of observers did not improve matters. These findings show that seven weekly measurements of lower leg length overestimate, whereas measurements of height underestimate, growth in the next three months.

**The weekly growth of children before and after tonsillectomy.** Six children measured weekly for three weeks before tonsillectomy had a mean (SD) increase in lower leg length of 0·12 (0·03) cm. In the

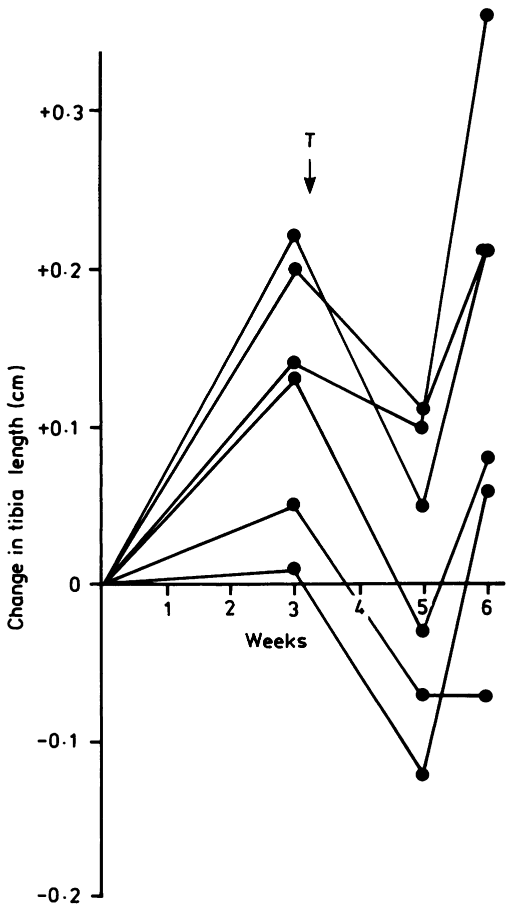


Fig. 3 *Change in lower leg length in six children measured by knemometry weekly for three weeks before tonsillectomy (indicated by T and arrow) and for three weeks thereafter. The lines joining the points at 0, 3, 5, and 6 weeks are the best fit.*

two weeks immediately after the operation there was a significant decrease in lower leg length of −0·11 (0·04) cm and in the sixth week of study there was catch up growth of +0·14 (0·06) cm. These observations are shown graphically in Figure 3.

## Discussion

The study was designed to answer three questions. Firstly, how good is the knemometer at measuring lower leg length? Secondly, how does the lower leg grow and what is its relation to growth in absolute height? And thirdly, can measurement of lower leg length in the short term be used to predict future growth and hence shorten the time needed to assess the efficacy of growth promoting treatment.

Earlier work reported that knemometry can document changes in lower leg length weekly, day by day, or even within a day.[1–3] (Valk IM. Personal communication.) We have confirmed some of these claims and have shown the device to be a precise, robust, and sensitive means of measuring changes in lower leg length. After a brief period of instruction observers quickly became proficient in the technique. We have shown that observers may interchange so long as care is taken in positioning the child in exactly the same manner from visit to visit; this adds practical flexibility to clinical measurement. The consistently low coefficient of variation between readings taken at a single visit by one observer meant that four observations were adequate for the determination of lower leg length. In this study the arithmetic mean of six or four observations was always used, but in future work we would recommend that four observations should be made and if one was deviant it should be discarded. A modal estimate of lower leg length will be as good as or better than the arithmetic mean. The answer to the first question is unequivocally favourable: the knemometer is an excellent tool for measuring lower leg length.

The precision of knemometry revealed an irregular pattern of lower leg growth from week to week, which was explicable in some cases, such as the children who suffered short illnesses or underwent tonsillectomy, but not in others. This meant that the precision of the technique in detecting small changes in lower leg length became a potential liability if the observer wished to use the measurements as an indicator of linear bodily growth overall. Different parts of the skeleton grow at different rates before and during puberty[5] and it was therefore not surprising that there was an indifferent correlation between growth of the lower leg and total height over six months. More noteworthy was the observation that there was little difference between height and lower leg increments in the value of measurements made over shorter time intervals than six months in the estimation of a six month velocity. The loss of predictive value in height measurements is inherent in the technique, whereas the loss of predictive value in lower leg measurements is due to the inherent irregularity of growth of the lower leg. Thus for the measurement of growth over six months or longer height is preferable to lower leg length because the technique is simpler, the apparatus less costly, and the clinician is interested in the overall stature of the patient.

Knemometry may have a place in the evaluation of short term changes in growth rate and thus be useful in assessing response to treatment. If used for this purpose it is important to have multiple observations—for example, five weekly readings over one month—to derive a lower leg length velocity before treatment and then a similar period of measurement on treatment. Used in this way knemometry could be used to screen patients, those responding to treatment in the short term then meriting a longer therapeutic trial monitored by conventional auxology.

We are grateful to the children and their parents who volunteered for this study, to Mrs S Amos, Mrs M Pickering, and Mrs C Grieve who made most of the measurements, and to Sanofi UK who provided the knemometer and financial support. Statistical advice from Dr I R Dunsmore of the department of probability and statistics, University of Sheffield, is acknowledged. Also our thanks to Mr P D Bull, Consultant ENT Surgeon, for allowing us to measure his patients.

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